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Detection of the 27 Aug 1998 Gamma Ray Flare, and Ionospheric Effects of Relativistic Electron Flux Enhancements

Timothy F. Bell

STAR Laboratory, 350 Serra Mall
Stanford University
Stanford CA 94305-9515

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STAR Laboratory, 350 Serra Mall
Stanford University
Stanford, CA 94305-9515

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Intense gamma ray flares and enhanced relativistic electron precipitation can have profound effects upon the characteristics of the nighttime D-region of the ionosphere. We examine recent examples of these phenomena and discuss their effects upon HAARP systems.

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Summary

This report considers the effect upon the nighttime ionospheric D-region of two separate phenomena: an intense gamma ray flash and enhanced relativistic electron precipitation in the subauroral region. Application is made to the HAARP HF heating facility and to the HAARP auroral electrojet diagnostic system.

Detection of the 27 August 1998 Gamma Ray Flare, and Ionospheric Effects of Relativistic Electron Flux Enhancements

1. Introduction

This Interim Technical Scientific Report for Contract F19628-96-C-0149 covers the period 10/01/97-09/30/98. During this period two notable scientific advances were made with the support of this contract which are directly relevant to the HAARP project. These advances are described below.

2. Detection of Gamma Ray Flare

On August 27th, 1998, at about 3:22 PDT (10:22 UT), an extremely intense gamma ray flare passed through the solar system, rapidly ionizing the exposed part o the Earths nightside upper atmosphere, producing ionization levels usually found only during the daytime. This gamma ray flare originated at a faint X-ray star, located in the distant reaches of our Galaxy, some 23,000 light years away. This star, known as Soft Gamma Repeater (SGR) 1900+14, is a new kind of star called a Magnetar; a dense ball of super heavy matter, no larger than a mountain but weighing more than the Sun, with a magnetic field far greater than known to exist anywhere else in the Universe. The flare lasted for about 5 minutes, and exhibited strong fluctuations at a rate of 5.16 seconds, believed to be rate of rotation of the spinning Magnetar.

The observation of the intense ionization of the nighttime ionosphere by this flare constitutes the first direct evidence of a physical effect on the Earths environment by a distant star, or by any star other than our own Sun. Ionization is the process by which

streams of energetic photons (those which constitute gamma rays and x-rays) knock electrons out of the atoms of air molecules and are absorbed in the process. The intense burst of gamma ray photons which impinged on our atmosphere during this event were absorbed at altitudes of 60 to 90 km. as they encountered the increasingly dense upper atmosphere. As they were absorbed, they ionized this region to a startling degree, to levels normally observed during daytime. The sudden appearance of this new ionization was observed via its effects on radio signals propagating from Hawaii to Colorado, and from Washington State to Colorado, alternately reflecting back-and-forth between the earths surface and the ionized regions of the upper atmosphere, known as the lower ionosphere.

The gamma ray flash event lasted for approximately 5 minutes, throughout which period the ionosphere remained ionized, roughly in proportion with the intensity of the burst. Careful analysis indicated that the ionization levels in the upper atmosphere exhibited a 5.16 second fluctuation, underscoring the fact that the upper atmosphere was dominantly under the influence of the gamma ray flare as it passed through the Earth.

This intense gamma ray flash was detected by the HAARP Auroral Electrojet Diagnostic System through its effects upon the VLF signals monitored at the Electrojet Diagnostic Systems sites. The portion of the Earth illuminated by the gamma ray flash is shown in Figure 1. Also shown in the figure are the propagation paths from the NPM, NLK, and NAA transmitter to receiving sites in the Midwest (HAIL array), the Antarctic (Palmer), and Boston. The Boston location is one of the HAARP electrojet diagnostic sites. The propagation paths most strongly affected by the gamma ray flash were the NPM-Boston and NPM-Palmer paths. Figure 2 shows the amplitude (upper panel) and phase (lower

panel) of the NPM signal received at the HAARP Boston site as a function of time over a 4 minute period which includes the time of the gamma ray flash at $\sim$ 1022 UT. The gamma ray flash produces a sudden amplitude decrease of $\sim$ 9 dB and a phase advance of $\sim 20°$. These changes are consistent with a sudden large increase in ionospheric electron density down to altitudes of $\sim$ 50 km.

The Boston gamma ray flash observations and those at Palmer and HAIL are being analyzed in detail and will be presented in a paper to be submitted for publication to Geophysical Research Letters.

3. Relativistic Electron Flux Enhancements

Relativistic electron flux enhancements in the magnetosphere on magnetic shells in the range $4 \leq L \leq 7$ occur regularly with a main period of $\sim$ 27 days due to recurring solar activity. Accompanying these flux enhancements is an enhancements in relativistic electron precipitation on these same L shells. This precipitation is quite intense and produces large increases in the electron density in the atmosphere down to $\sim$ 50 km. These large electron densities can result in significant absorption of HF waves radiated by the HAARP facility at frequencies less than 5 MHz, and thus can potentially disrupt HF experiments at HAARP using this frequency range. Consequently it is important to model the relativistic electron precipitation events to plan mitigation and to accurately predict the state of the ionosphere over HAARP. As a first step in this action we have modeled the effects of the energetic electron precipitation on the D-region and have compared the predicted results with observations. This work is reported in a paper published in the Journal of Geophysical Research December 1999, and is included in the Appendix.

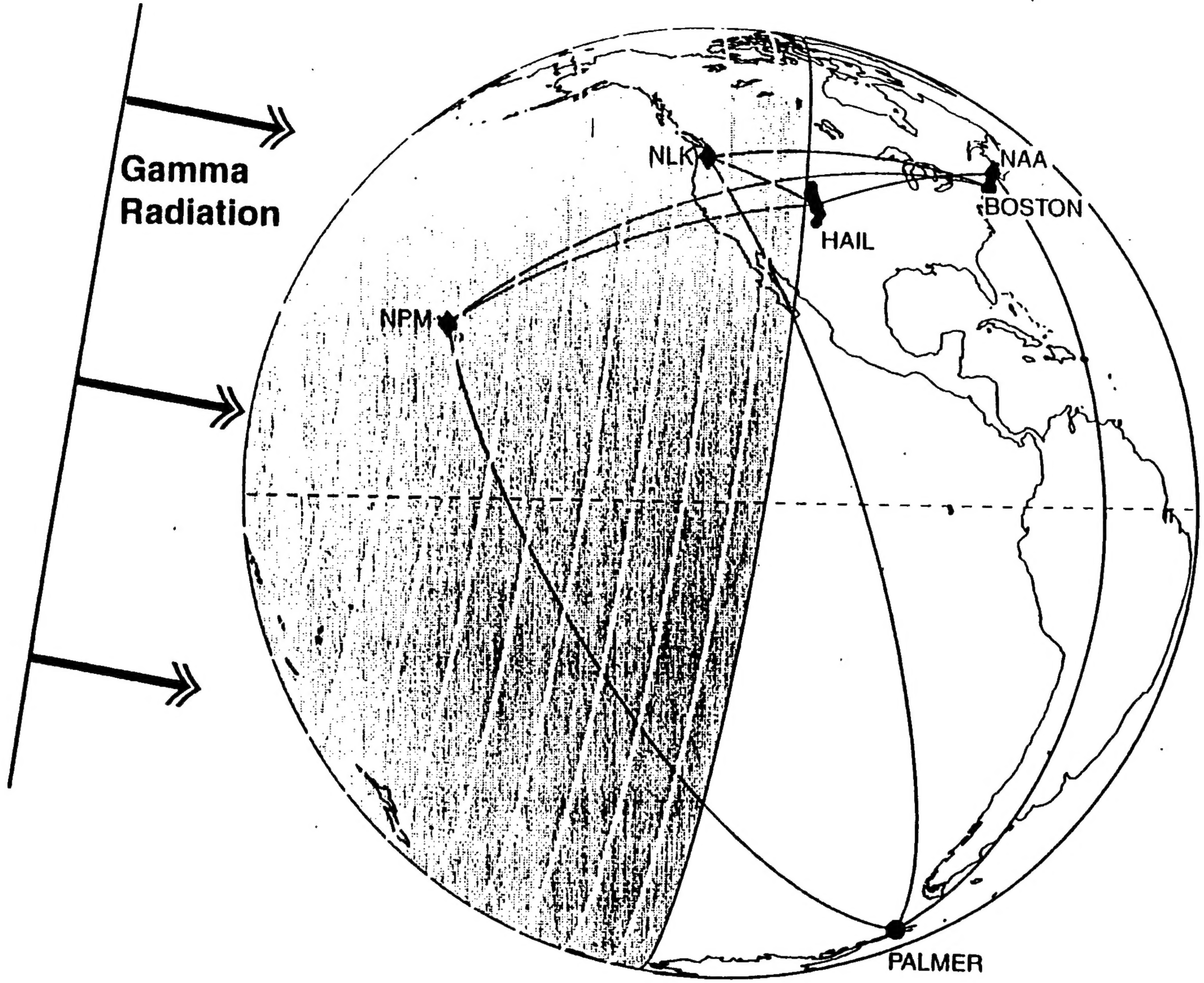

Figure 1. Illustration showing the portion of the Earth illuminated by the intense gamma ray flash on August 27, 1998 at 1022 UT. Approximately two-thirds of the propagation path between NPM in Hawaii and the HAARP site in Boston was disturbed by the flash.

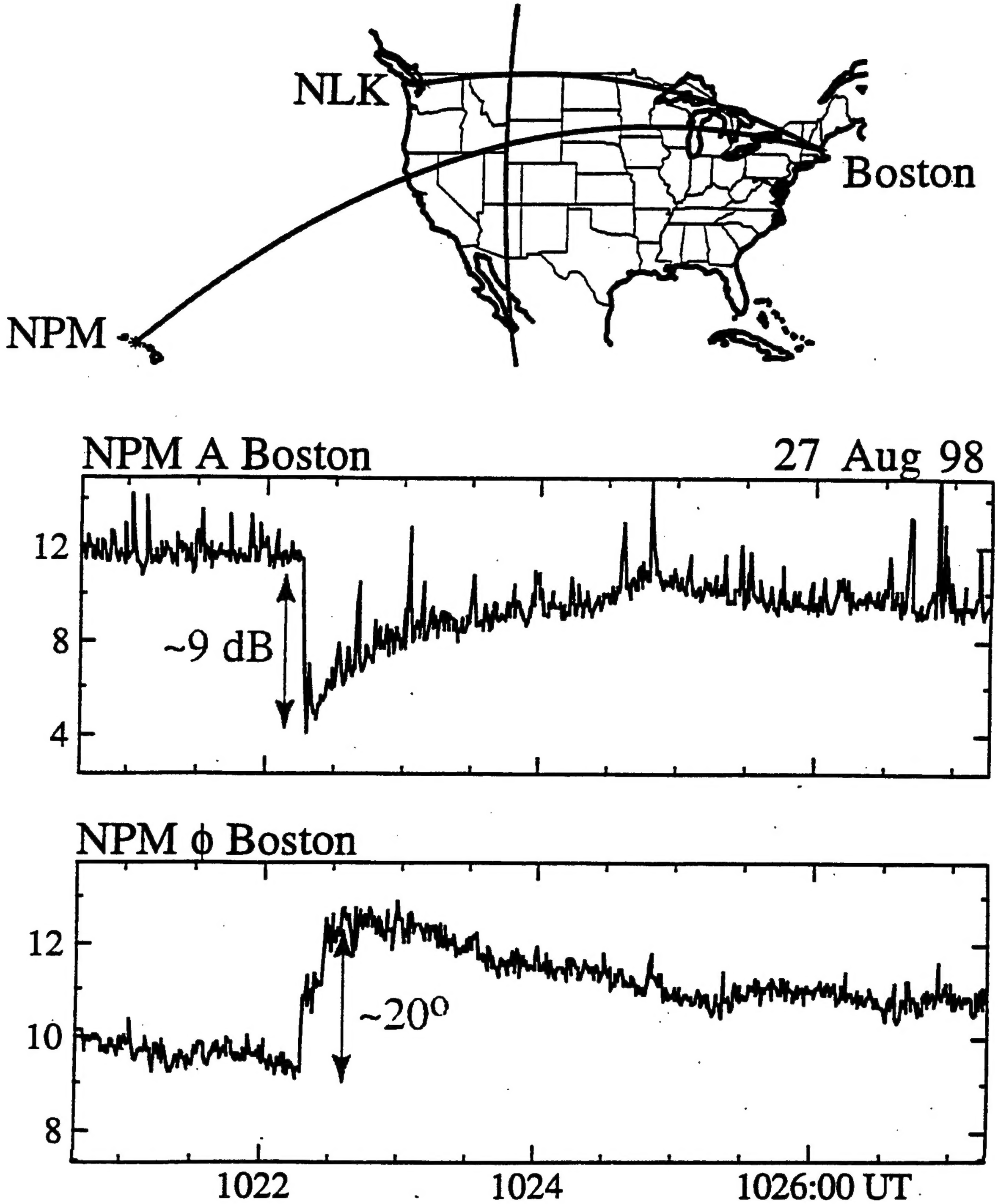

Figure 2. Amplitude and phase records of the NPM signal as observed in Boston during the time of the gamma ray flash. At approximately 1022:10 UT when the flash first strikes the Earth, the NPM amplitude shows a sudden decrease of 9 dB due to increased absorption along the subionospheric propagation path. At the same time the phase shows an increase of 20 degrees due to a lowering of the D-region reflection height.

Appendix 1

Ionospheric Effects of Relativistic Electron Enhancement Events

Mehmet K. Demirkol. Umran S. Inan, Timothy F. Bell
Space, Telecommunications and Radioscience Laboratory, Stanford University, Stanford, CA 94305

S. G. Kanekal
Goddard Space Flight Center, Greenbelt, MD 20771

D. C. Wilkinson
National Geophysical Data Center, 325 Broadway Boulder, CO 80303

Abstract. The relativistic electron population as measured both at geosynchronous orbit and at low altitudes at subauroral latitudes exhibits pronounced fluctuations in association with magnetospheric substorm and solar activity. A ground-satellite correlative study based on amplitude and phase measurements of VLF signals propogating in the earth-ionospheric waveguide indicates that the relativistic electron enhancements are accompanied by similar enhancements in nighttime ionospheric conductivity produced by associated enhanced precipitation. VLF signal amplitudes are found to exhibit < 10 dB changes, showing the same 27 day cycle and 2-3 day rise and fall time pattern as relativistic electron enhancement events recorded by GOES 7 and SAMPEX, and indicating that the nighttime lower ionospheric electron density at subauroral latitudes is detectably affected by 27-day periodicity in solar rotation.

1. Introduction

The Earth's outer magnetosphere is often populated to a surprising degree by relativistic electrons [*Paulikas et al.*, 1979]. Enhancements in the relativistic electron fluxes may be an important source of energy input to the atmosphere. Those precipitating electrons with energies > 1 MeV can penetrate to altitudes as low as 50 km, affecting the atmospheric chemistry throughout the mesosphere [*Gaines et al.*, 1995]. Relativistic electron precipitation events are also believed to be a significant source of odd nitrogen in the middle atmosphere, possibly affecting ozone concentrations in some regions of the atmosphere [*Callis et al.*, 1991]. Relativistic electron precipitation events are associated with magnetospheric activity and may appear more frequently near a solar minimum than solar maximum [*Baker et al.*, 1986]. These events are strongest at subauroral ($4.5 < L < 7$) latitudes. The enhancements of energetic particle fluxes within and near the local loss cone are documented in data from low altitude satellites such as SAMPEX [*Baker et al.*, 1993] and UARS [*Gaines et al.*, 1995], while the relativistic electron population at geosynchronous orbit is measured on GOES-7 and GOES-8. The particle flux as measured on these satellites exhibit the well known relatively regular 27-day periodicity with typical rises on a 2- to 3- day time scale and decays on a 3- to 4-day scale [*Baker et al.*, 1986].

Very Low Frequency (VLF) sounding of the lower ionosphere (i.e., the measurement of the amplitude and phase of subionospherically propagating VLF signals) is a sensitive tool for the detection of ionospheric conductivity changes due to changes in electron density and/or temperature, especially at altitudes below 90 km [*Sechrist et al.*, 1974]. Some of the early work on relativistic electron precipitation events has indeed relied on subionospheric

VLF measurements [*Thorne et al.*, 1976].

In this paper we use the VLF method to quantitatively assess the degree to which relativistic electron enhancements observed at satellite altitudes are accompanied by enhanced precipitation into the ionosphere. We search for the ionospheric signatures of relativistic electron precipitation by interpreting the observed VLF amplitude variations in the light of theoretical models of VLF subionospheric wave propagation [*Poulsen et al.*, 1993]. Our results indicate that the nighttime D-region is indeed strongly affected by this precipitation, with the electron density at 40-70 km altitudes clearly exhibiting the 27-day cycle associated with solar rotation.

2. Description of data

For this study, we focus our attention on the two month period of October and November 1992 (for which VLF data from Fort Yukon is continuously available and utilize three different data sets, namely (i) VLF data, (ii) SAMPEX data, and (iii) GOES 7 data. Each of these data sets is briefly described below.

2.1 Ground based VLF data

The VLF data consists of the recorded amplitude and phase of the subionospheric signal from the NLK transmitter (24.8 kHz) in Jim Creek, Washington (121.91°W, 48.20° N) as received at Fort Yukon (FY), Alaska (145.218°W, 66.56°N) during the period Oct-Nov 1992. Figure 1 shows the NLK-FY great circle propagation path as well as lines of constant geomagnetic latitude. Since the fluxes of relativistic electrons exhibit fluctuations primarily at subauroral latitudes ($4.5 < L < 7$), the NLK-FY path is well situated for monitoring the ionospheric affects of these relativistic electron enhancements.

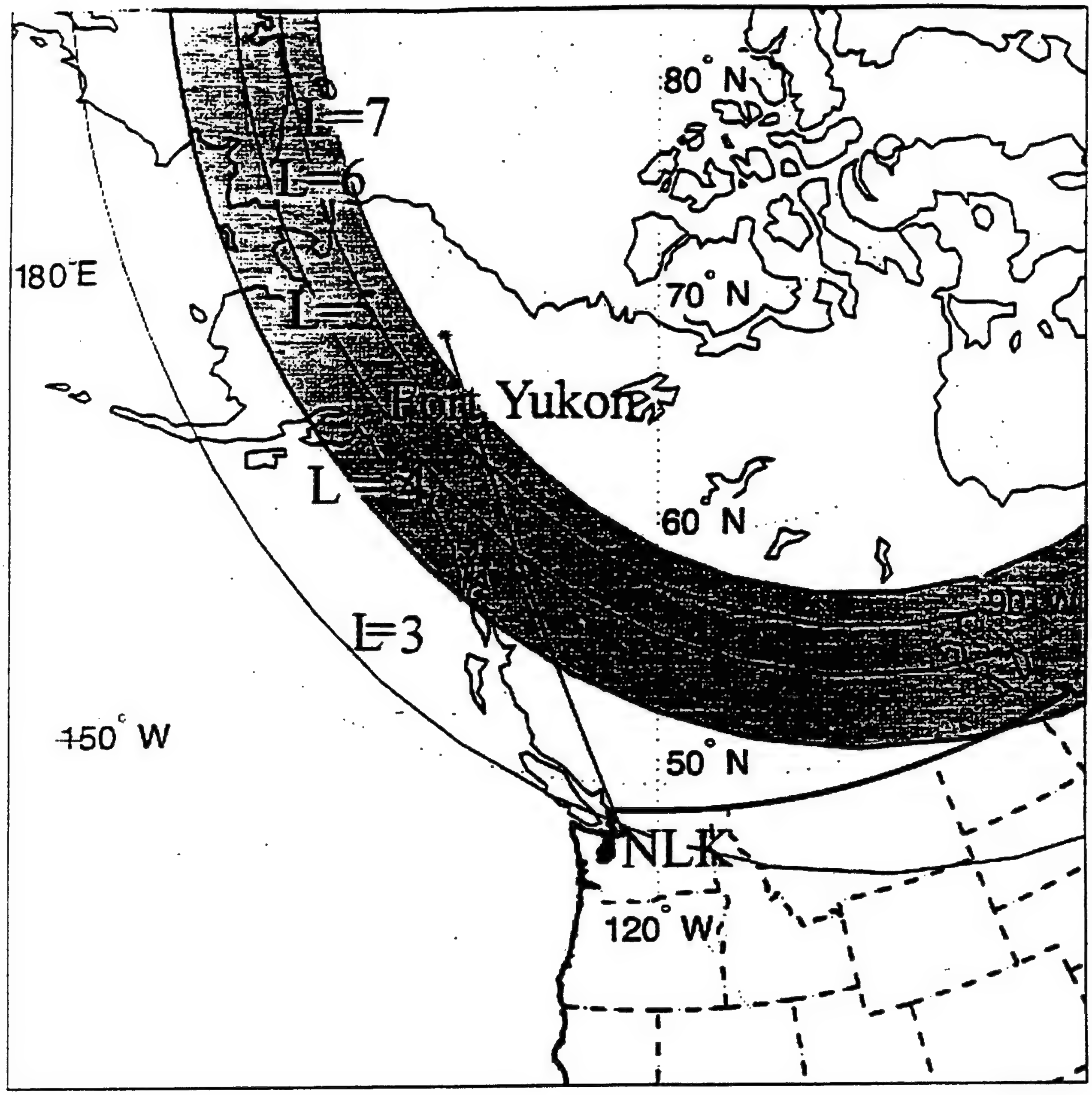

Figure 1. A geographic view of the VLF propagation path from NLK to Fort Yukon, Alaska. The NLK-FY path is situated such that the relativistic precipitation region (shown shaded) covers a significant portion of the great circle propagation path.

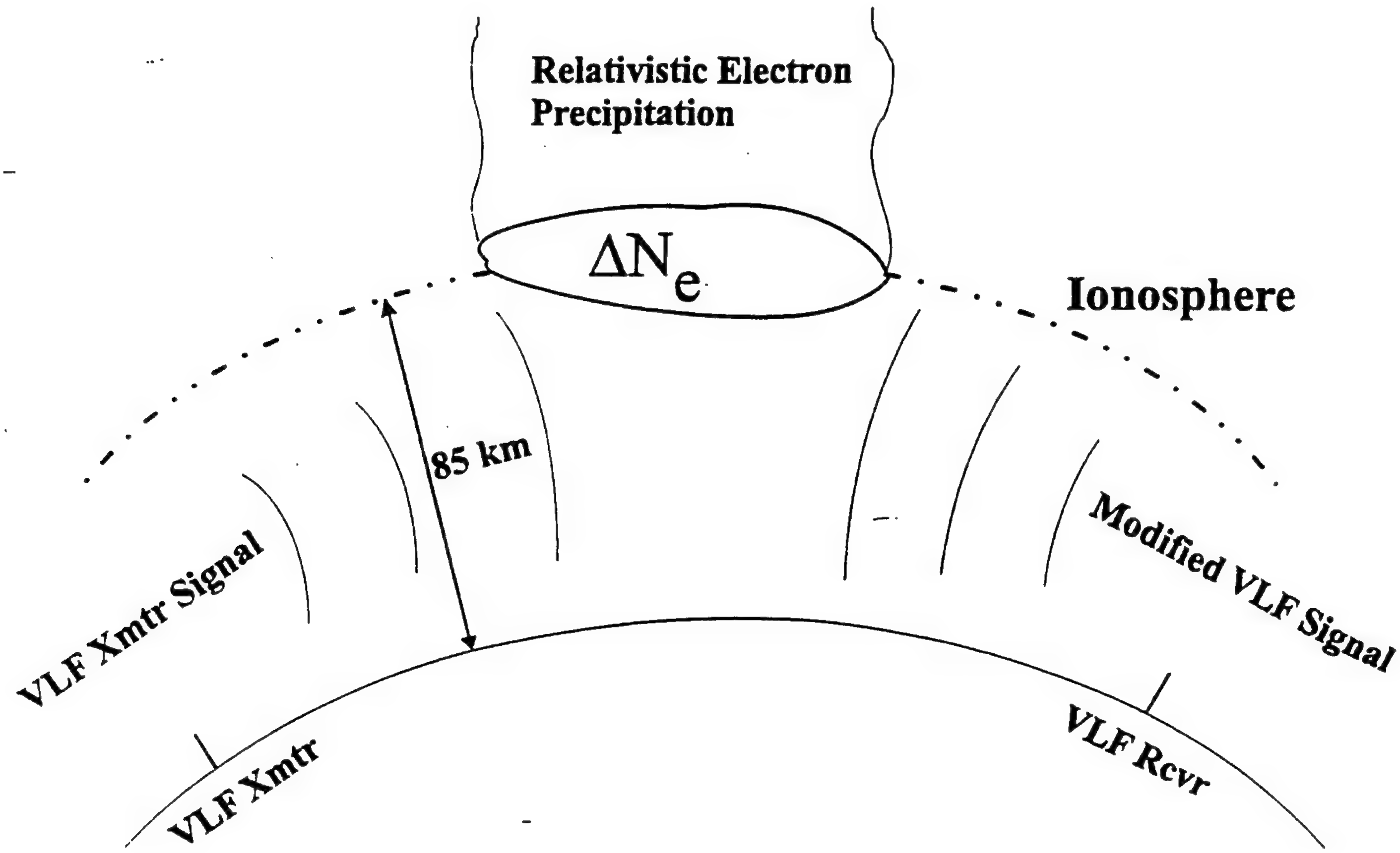

Figure 2. The mechanism of the particle precipitation-VLF interaction is schematically shown above. A ground VLF transmitter (T) launches a signal into the Earth-Ionosphere waveguide. In the region of relativistic particle precipitation the local electron density is increased by ΔNe and the local collision frequency is increased by $\Delta\nu$. The changes cause the local electrical conductivity to change. The waveguide signal propagating under the region of relativistic electron precipitation is modified in response to the conductivity changes, allowing the observation of this conductivity change as phase and amplitude variations in the VLF signal.

Subionospheric VLF signals are known to be very sensitive to D-region ionospheric parameters [*Galejs et al.*, 1972]. Increases in the D-region electron density caused by the high-energy particle precipitation increases the local electrical conductivity and perturbs the VLF signal propagating under the disturbed ionosphere. Figure 2 shows a schematic description of this process.

The VLF data at FY during the Oct-Nov 1992 period was typically recorded during the period 0000 to 1200 UT. The signal amplitude in a 300 Hz band centered at the transmitter frequency (24.8 kHz) is regularly sampled and digitally recorded at a resolution of 100 Hz (i.e., samples taken at 10 ms intervals). Since the VLF signal amplitude can exhibit significant variation over short time scales, for example in response to burst precipitation effects [*Cotton et al.*, 1991] or auroral electrojet enhancements [*Cummer et al.*, 1996], studies of long term behavior are facilitated through the use of data averaged over a number of hours on each day. For this purpose we have chosen to average the VLF data over the time interval 0600 to 0900 UT each day, during which the entire NLK-FY path was under darkness throughout the study period. For each day, this simple 3 hour average of the signal amplitude is designated as the 'average' signal amplitude.

2.2 SAMPEX and GOES data

The details of the energetic particle instruments with which SAMPEX and GOES satellite data were acquired are described elsewhere. We provide a brief summary below.

The Proton/Electron Telescope (PET) [*Cook et al.*, 1993] on SAMPEX is composed of an array of silicon solid state detectors that identify and measure the kinetic energy of electrons from 1 to 30 MeV and of H and He isotopes from 20 to 80 MeV/nuc. The

SAMPEX data used in this paper are integral fluxes of > 4MeV electrons measured in specific passes nearby the subionospheric paths.

The GOES-8 Energetic Particle Sensor (EPS) measures electrons from 0.6 to greater than 4.0 MeV, protons from .8 to 500 MeV, and alpha-particles from 4 to 500 MeV [*Goes Operations Handbook*, 1994]. The electron measurements are made via solid state surface barrier detectors within a dome subassembly. The data used in this paper are 5-minute averages of the integral fluxes of > 2 MeV electrons.

3. Ground and Satellite Data Comparisons

The 'averaged' VLF amplitude for the October and November 1992 period is compared in Figure 3 with the corresponding satellite particle data measured by GOES-7. The GOES-7 electron flux maxima are clearly associated with the amplitude minima in the VLF data. A 27-day cycle is clearly apparent in the VLF data, similar to that observed in GOES data for the relativistic electron enhancement events, with the same 3-4 days of rise and fall times. In association with the two large electron flux enhancements which peak on days 276 and 305, the VLF signal amplitude exhibits changes > 9 dB with rise and fall times of a few days. The VLF amplitude minima are delayed by about two days with respect to the peaks in GOES data; possible reasons for this delay are discussed later. The two smaller peaks in the GOES data, which are an order of magnitude below the two main peaks, are not associated with strong VLF amplitude minima.

To our knowledge this is the first observation of a subionospheric VLF amplitude variation exhibiting the same 27-day cycle as the relativistic electron enhancements events, thus indicating that the nighttime lower ionospheric electron density is detectably affected by

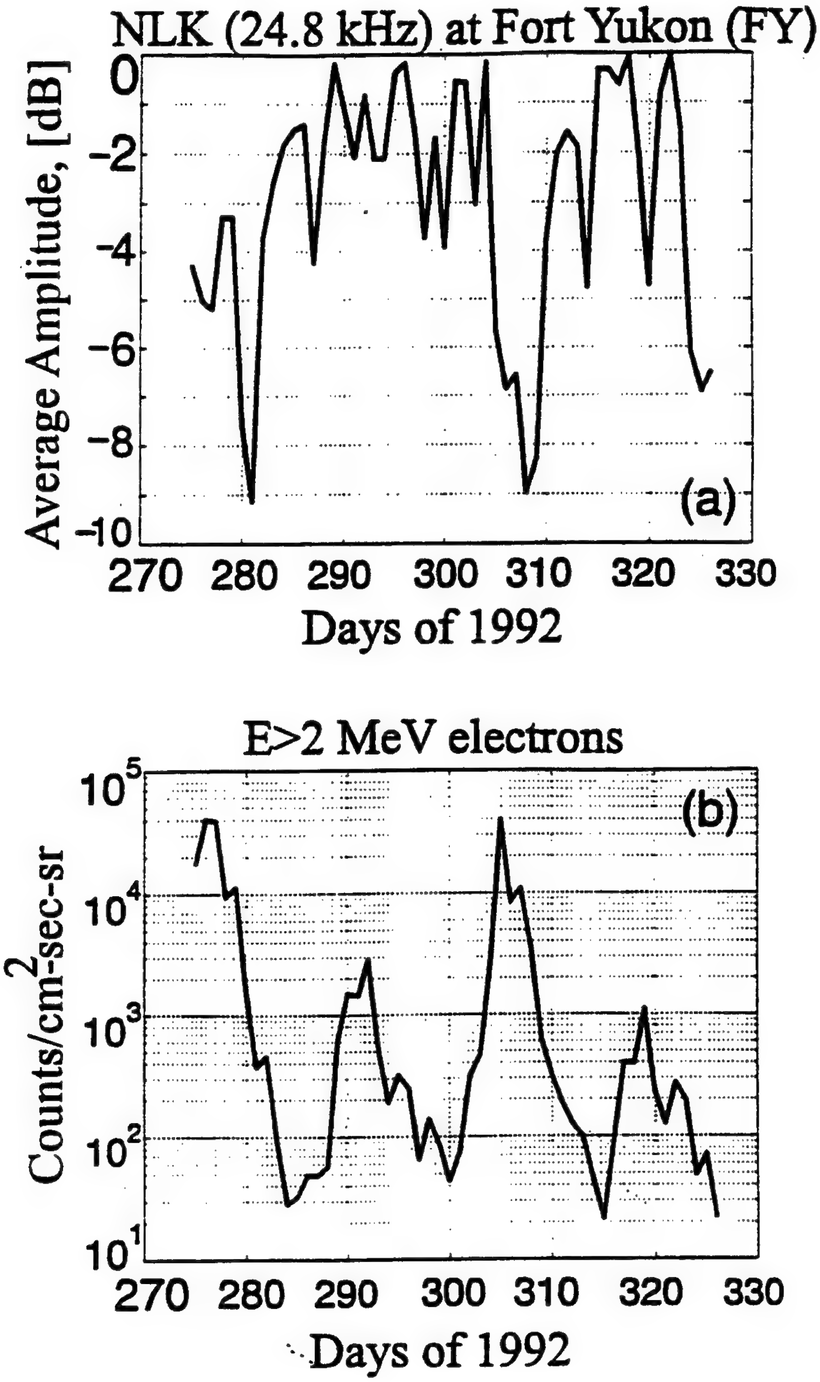

Figure 3. **(a)** The three-hour-averaged amplitude of the NLK signal (24.8 kHz) at Fort Yukon (FY) on each day. **(b)** Electron precipitation flux as measured on GOES 7. A 27 day variation is apparent in each data set.

the solar rotation. We note that since we use 3 hr averages of the VLF data, any measurement noise in the 300 Hz VLF channel is completely removed, and the daily variations shown in Figure 3a are true indications of day to day changes in the lower ionosphere, principally due to auroral effects and long term precipitation associated with the auroral electrojet [*Cummer et al.*, 1996]. The 27 day variation is clearly the dominant effect, imposed on top of these other variations. At the same time the variability of the nighttime ionosphere due to the other auroral effects probably accounts for the lack of a VLF amplitude minima associated with the smaller peak in the GOES data near day 292 (Figure 3). Using the three-hour-averaged amplitude, it appears that only relativistic electron enhanced flux levels above $\sim 3 \times 10^3$ el/cm^2-sr-s produce ionospheric effects that stand out in the presence of other ionospheric variations.

4. Model Calculations

The coincident occurrence of subionospheric VLF signal changes and relativistic electron enhancement peaks suggest that significant enhanced precipitation accompanies the enhancement events. In order to determine whether the observed VLF amplitude signatures are consistent with the ionospheric changes expected to be produced by such relativistic electron precipitation, we theoretically model the propagation of the VLF signal in the earth-ionosphere waveguide along the great circle path from NLK to FY. For this purpose, we use the Long Wave Propagation Capability (LWPC) code [*Ferguson et al.*, 1987]. The disturbance along the NLK-FY propagation path is modeled as a segment of the Earth-Ionosphere waveguide with a perturbed electron density profile caused by relativistic electron precipitation. Figure 4a and 4b show perturbed electron density profiles associated

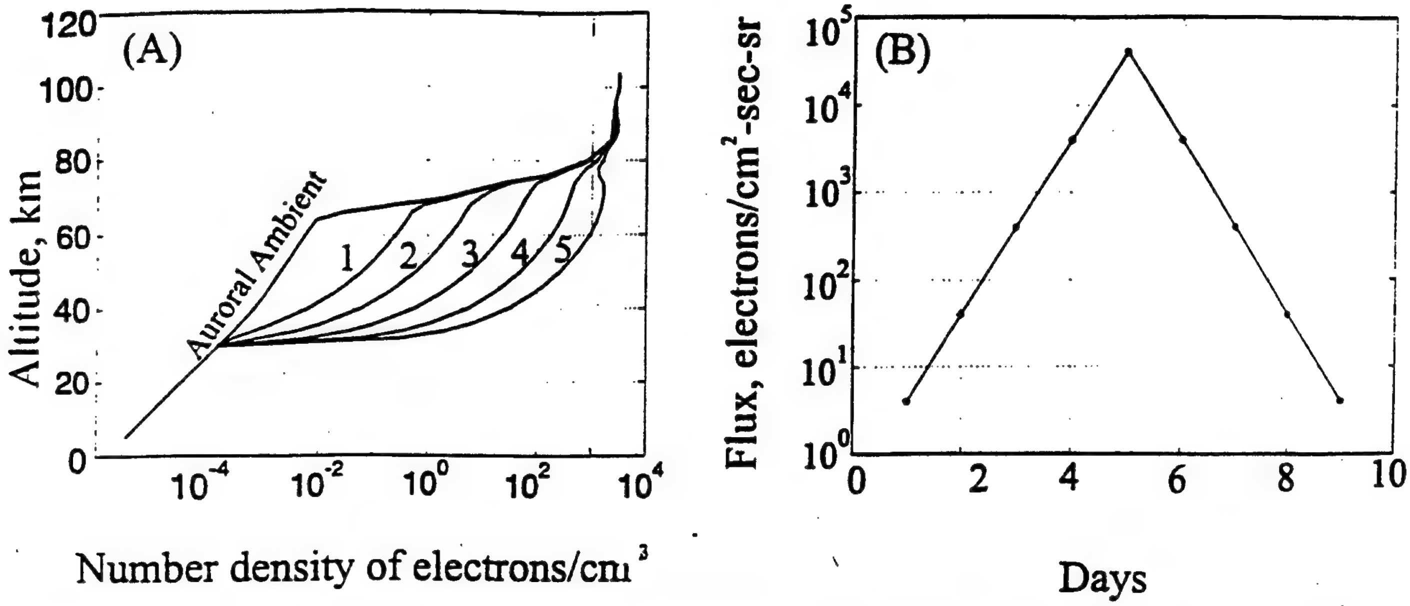

Figure 4. **(a)** Ionization profiles corresponding to the different levels (1, 2, 3, 4, 5) of relativistic electron precipitation fluxes as shown in **(b)** A typical relativistic electron precipitation enhancement, shown here rising and falling in 9 days. In most cases event durations are as much as 10-15 days. The flux levels and energy spectra of the precipitation was taken to be as given by Gaines et al. [1994], based on measurements on the UARS satellite.

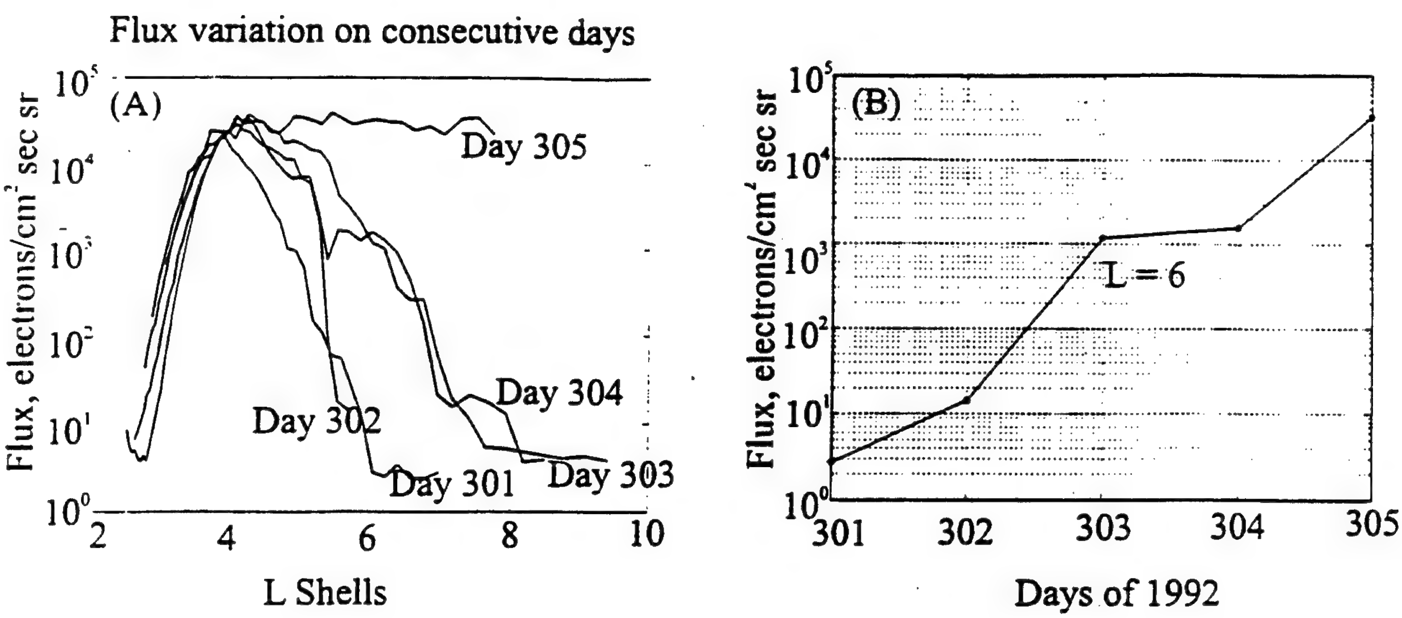

Figure 5. **(a)** Integral flux of >4 MeV electrons measured as each day by SAMPEX during passes nearest (in longitude) to the NLK-FY path. The largest flux variation occurs near L≈ 6. **(b)** Flux level at L=6 as a function of day.

with different flux levels as determined by the method of *Gaines* et al. [1994]. Energetic electron data from SAMPEX, specifically the integral flux of > 4 MeV electrons, which was recorded during passes when the satellite was closest (in longitude) to the propagation path, is used in order to have the best estimate of electron flux levels in the ionospheric region which lies above the VLF path. A time period in the vicinity of the peak in relativistic flux on day 305 was chosen for this purpose. There are two notable characteristic of the flux enhancements shown in Figure 5a. First, we note that the largest flux level changes occur between $5<L<7$. Second, we note a significant spatial expansion of the disturbed region following day 304 which covers an increasingly larger segment of the NLK-FY path. This spatial expansion is the likely reason for the $\sim$2 day delay of the VLF amplitude minima with respect to the relativistic enhancement peak which was noted earlier in connection with Figure 3. Note that the VLF amplitude change is proportional to the electron enhancement as well as the path segment affected [*Inan et al.*, 1987].

For the VLF propagation model calculations, the propagation path NLK-FY was segmented using electron density profiles associated with the actual flux levels shown in Figure 5a. Figure 5b shows flux levels used in our model as derived from SAMPEX data for $L \simeq 6$. LWPC code calculations were carried out using these models of the ionospheric disturbance. The results shown in Figure 6 predict $\sim$7 dB maximum amplitude decrease, which compares generally well with the observed 9 dB signal amplitude decrease. The somewhat lower calculated amplitude change may be due to the fact that the $>$4 MeV electron flux used to determine the associated electron density profiles, underestimated the relativistic electron enhancements which generally involve electrons with energies $>$0.5 MeV.

5. Conclusions

Comparison of VLF amplitude data with GOES-7 and SAMPEX data on relativistic electron flux levels show a clear association between the two data sets in the case of two successive relativistic electron enhancement episodes for which VLF data is available. The VLF amplitude and particle flux levels measured on GOES-7 show the same 27 day cycle and 2-3 days of rise and fall times for a characteristic relativistic precipitation enhancement event. VLF signal amplitudes exhibited >9 dB decreases associated with the electron flux level enhancements indicating that the nighttime electron density at 40-70 km altitudes is strongly influenced by the solar rotation, via the relativistic electron enhancement events driven by the solar wind. The ionospheric effect of the relativistic electron enhancements was observed only when the flux was above 3×10^3el/cm^2-sr-s, apparently because of the fact that the VLF signature of the enhancement for lower fluxes is suppressed by other ionospheric variations.

Comparison of our VLF observations with theoretical predictions of amplitude decreases of >7 dB obtained using propagation model calculations provides satisfactory agreement. Calculations also show that the amplitude change associated with the lower peaks of the relativistic electron enhancement are less than 1 dB, not observable in the presence of larger ionospheric variations associated with auroral effects.

We conclude on the basis of both observation and the theoretical analysis presented here that the conductivity of the nighttime lower ionosphere at subauroral latitudes is strongly modulated by the relativistic electron precipitation which accompanies relativistic electron enhancements. High-energy precipitation causes electron density enhancements in the D

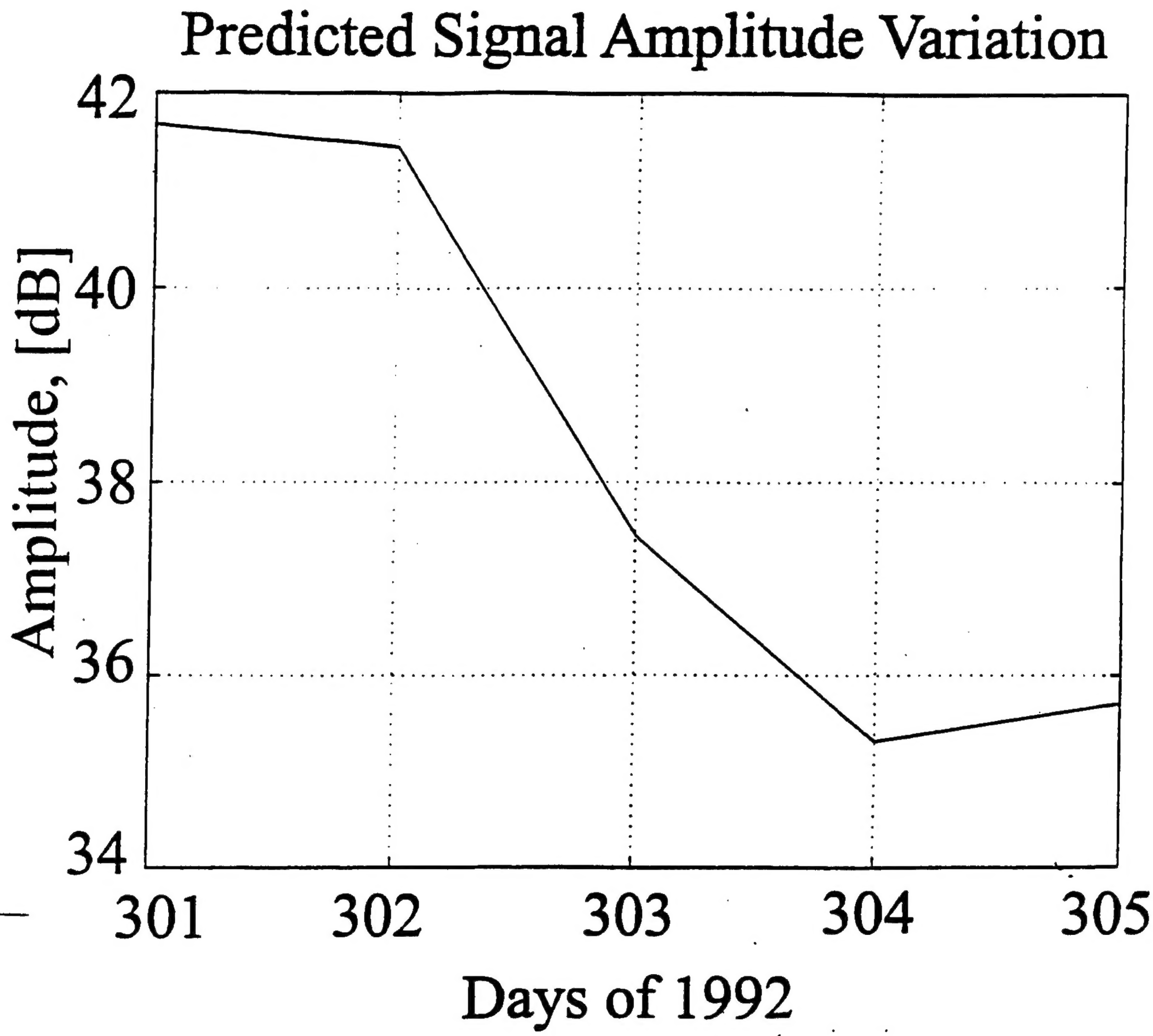

Figure 6. The predicted NLK signal amplitude variation as observed at Fort Yukon.

region of the ionosphere, which in turn affect VLF waves propagating in the perturbed Earth-Ionosphere waveguide. This realization also provides the first evidence of a detectable influence on the nighttime lower ionosphere of solar rotation, imposing a 27-day cycle on top of other variations of this region of our atmosphere.

Our results further indicate that VLF remote sensing can be a powerful tool for investigation of relativistic electron flux enhancements and their ionospheric and mesospheric effects. A system with multiple receiving stations observing VLF signals that cross the affected regions (see Figure 2) could be used to assess the spatial distribution of precipitation as well as the precipitation flux levels.

Acknowledgments

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T. F. Bell, M. K. Demirkol, and U. S. Inan, Space. Telecommunications and Radioscience Laboratory, Stanford University, Stanford, California (e-mail:bell@nova.stanford; mdemirkol@nova.stanford.edu; inan@nova.stanford.edu)

S. G. Kanekal, Goddard Space Flight Center (e-mail: kanekal@lepsam.gsfc.nasa.gov)

D. C. Wilkinson, National Geophysical Data Center (e-mail:dwilkinson@ngdc.noaa.gov)

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